Non-equilibrium collective dynamics in high-energy heavy ion collisions

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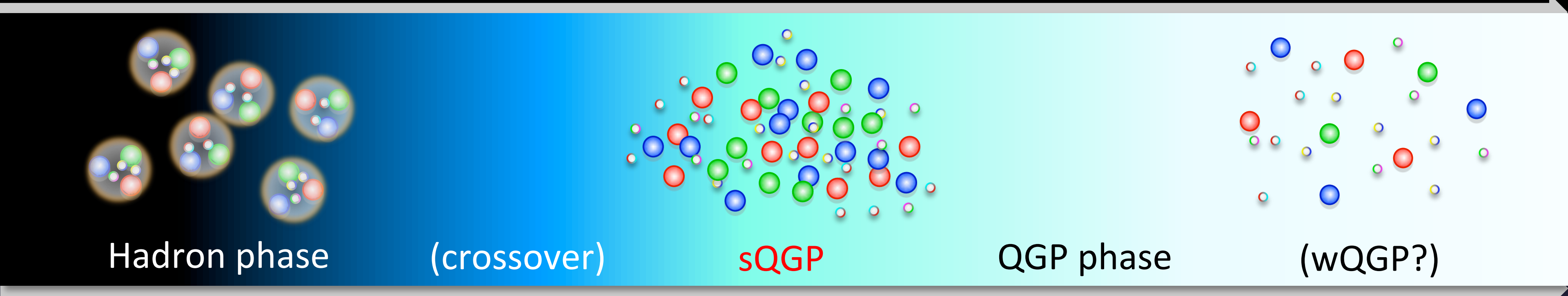
Overview

1. Introduction
   - The quark-gluon plasma
   - High-energy nucleus-nucleus collisions
2. Dissipative hydrodynamics of QGP
   - Thermodynamic variables
   - Relativistic dissipative hydrodynamics with charge densities
   - Baryon stopping
3. Center domain structure in QGP
   - Quark contribution to fluidity and opacity
   - Discussion
4. Summary and outlook

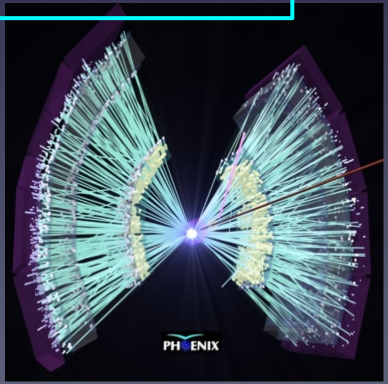
Introduction

- Quark-gluon plasma (QGP): many-body system of deconfined quarks and gluons

Graphics by AM



The QGP is supposed to have filled the early universe;
It can be produced in heavy ion experiments at RHIC & LHC

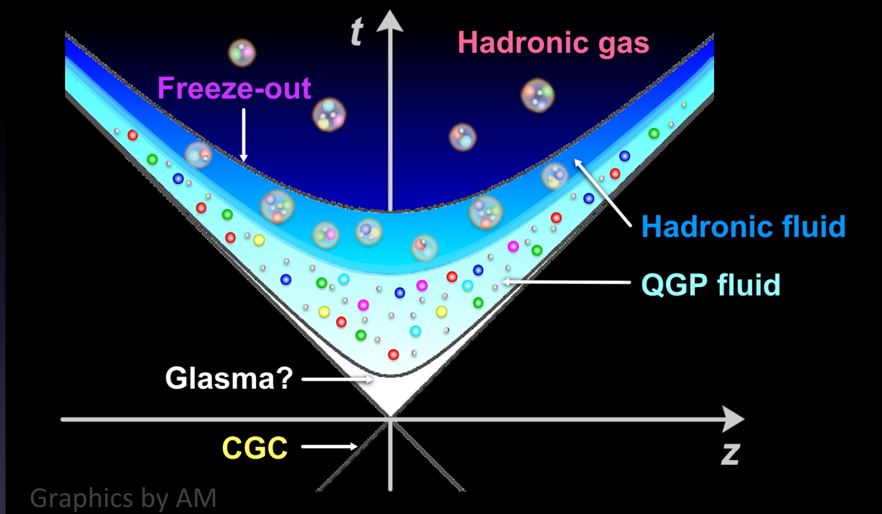


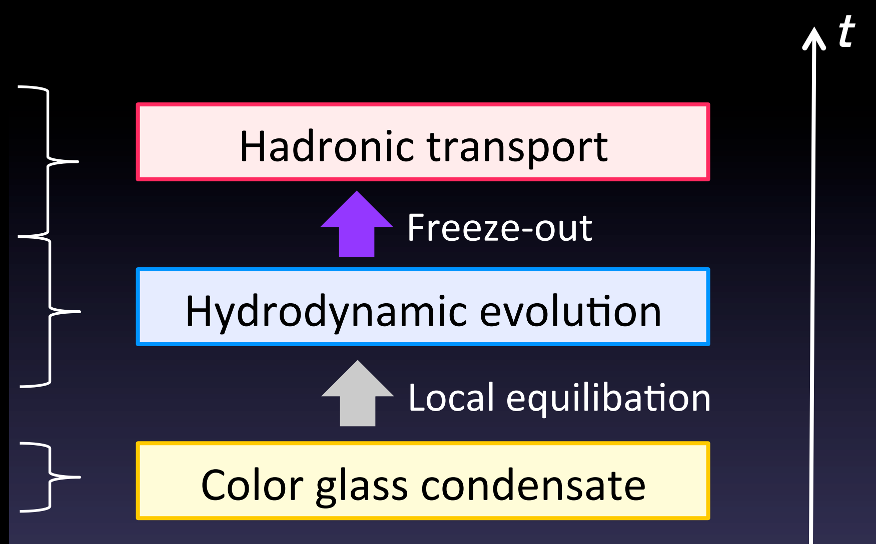
⇨ Heavy ion QGP is characterized with…

- Near-perfect fluidity (thermalized)
- Large color opacity

Introduction

- "Standard model" of high-energy heavy ion collisions





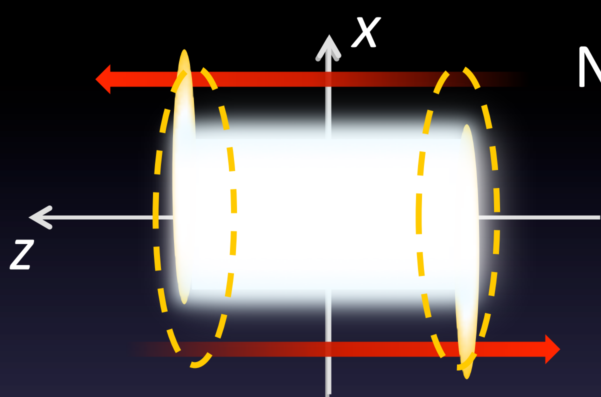
- τ < 0 fm/c: color glass condensate (saturated gluons)
- τ ~ 0-1 fm/c: glasma? (pre-equilibrated medium)
- τ ~ 1-10 fm/c: QGP/hadronic fluid (strongly-coupled medium)
- τ > 10 fm/c: hadronic gas (weakly-coupled medium)

2. Dissipative hydrodynamics of QGP

Reference: AM, Phys. Rev. C **86**, 014908 (2012)

Motivation

- Analyze hydrodynamic QGP at finite baryon density with shear viscosity + bulk viscosity + baryon diffusion

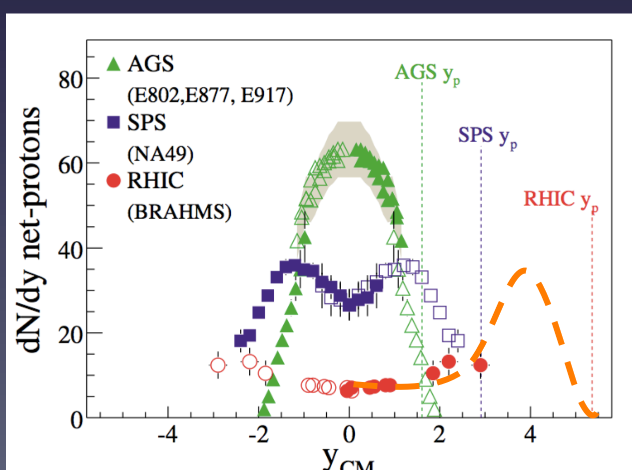


Net baryon is conserved at forward rapidity

- Precision physics including particle identification (p/$\overline{\text{p}}$ ratio, etc.)
- Finite-density transport properties

- Baryon stopping

Plot: BRAHMS, PRL 93, 102301 (2004)

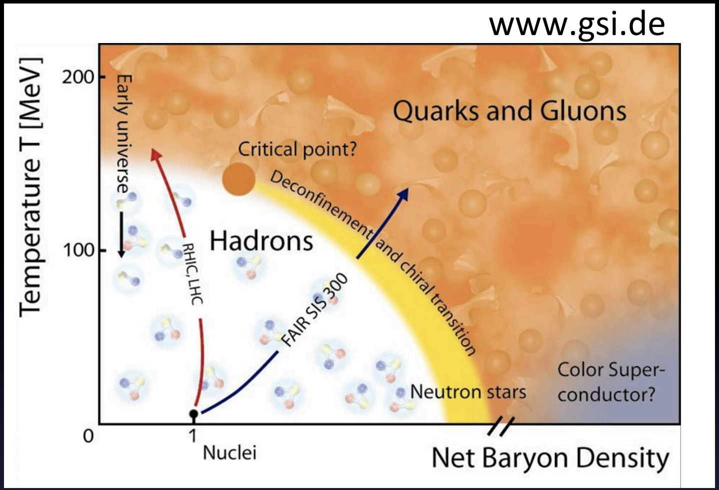


Baryon stopping can quantify kinetic energy available for QGP production

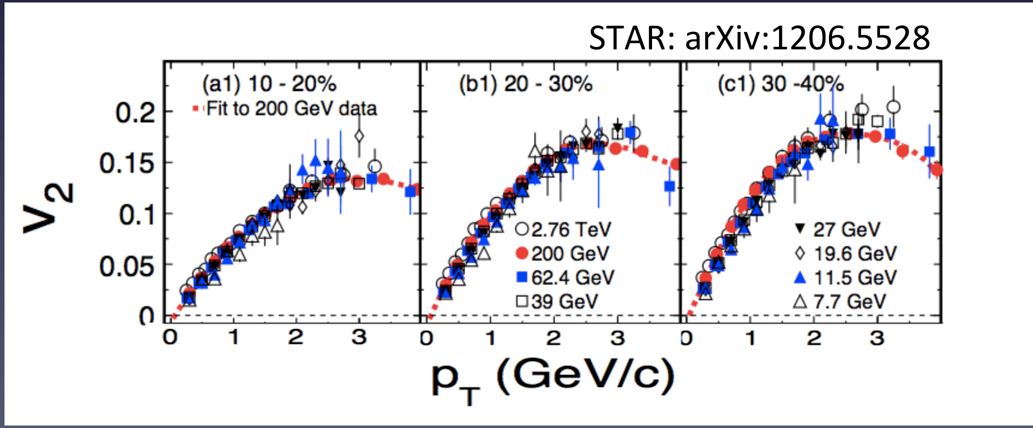
mean rapidity loss $\langle \delta y \rangle$
= rapidity of projectile nuclei y_b
– mean rapidity of net baryon $\langle y \rangle$

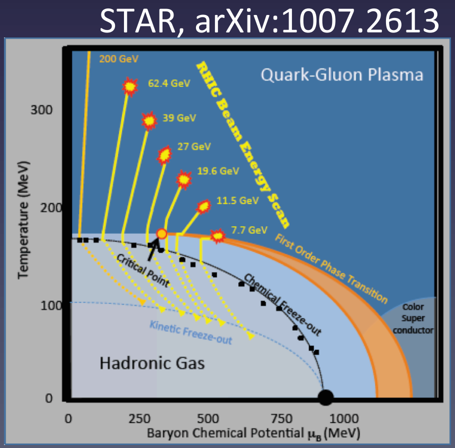
Motivation

- Exploring the QCD phase diagram
  - Finite baryon density is a *difficult* issue in first-principle calculations
    - ⇨ Hydrodynamics can be a help in the exploration



  - Beam energy scans for critical point search (at RHIC, FAIR, NICA, …)





⇨ Large v2 are observed at lower energies

Thermodynamic quantities

- In local rest frame $u^\mu = (1,0,0,0)$

$$T^{\mu\nu} = T_0^{\mu\nu} + \delta T^{\mu\nu}$$

$$= \begin{pmatrix} e_0 & 0 & 0 & 0 \\ 0 & P_0 & 0 & 0 \\ 0 & 0 & P_0 & 0 \\ 0 & 0 & 0 & P_0 \end{pmatrix} + \begin{pmatrix} \delta e & W^x & W^y & W^z \\ W^x & \Pi + \pi^{xx} & \pi^{xy} & \pi^{xz} \\ W^y & \pi^{yx} & \Pi + \pi^{yy} & \pi^{yz} \\ W^z & \pi^{zx} & \pi^{yz} & \Pi + \pi^{zz} \end{pmatrix}$$

$$N_J^\mu = N_{J0}^\mu + \delta N_J^\mu \quad (J = 1,2,\ldots,N)$$

$$= \begin{pmatrix} n_{J0} \\ 0 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} \delta n_J \\ V_J^x \\ V_J^y \\ V_J^z \end{pmatrix}$$

2+N equilibrium quantities

Energy density: e_0

Hydrostatic pressure: P_0

J-th charge density: n_{J0}

10+4N dissipative currents

Energy density deviation: δe

Bulk pressure: Π

Energy current: W^μ

Shear stress tensor: $\pi^{\mu\nu}$

J-th charge density dev.: δn_J

J-th charge current: V_J^μ

Thermodynamic quantities

- In general frame

$$T^{\mu\nu} = (e_0 + \delta e)u^\mu u^\nu - (P_0 + \Pi)\Delta^{\mu\nu} + W^\mu u^\nu + W^\nu u^\mu + \pi^{\mu\nu}$$

$$N_J^\mu = (n_{J0} + \delta n_J)u^\mu + V_J^\mu$$

$$\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$$

10+4*N* dissipative currents

Energy density deviation: δe
Bulk pressure: Π
Energy current: W^μ
Shear stress tensor: $\pi^{\mu\nu}$
J-th charge density dev.: δn_J
J-th charge current: V_J^μ

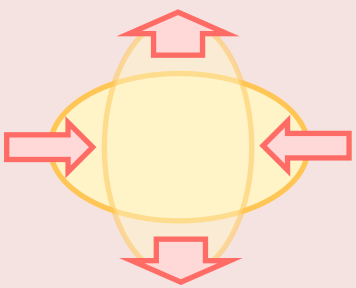
2+*N* equilibrium quantities

Energy density: e_0
Hydrostatic pressure: P_0
J-th charge density: n_{J0}

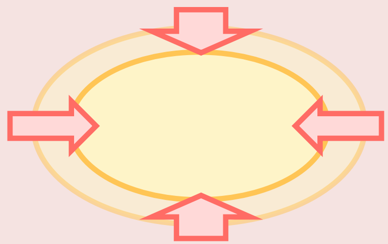
Thermodynamic quantities

- Meaning of “dissipation” in fluids

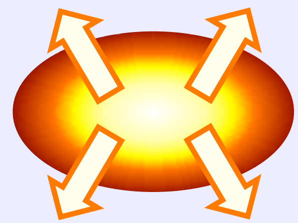
Off-equilibrium processes at linear order



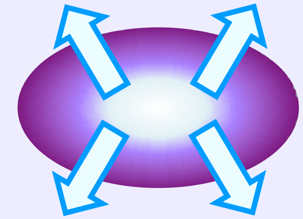
Shear viscosity
= response to
deformation



Bulk viscosity
= response to
expansion



Energy dissipation
= response to
thermal gradient



Charge dissipation
= response to
chemical gradients

viscosity

dissipation

- Cross terms among thermodynamic forces are present (discussed later)
- 2nd order corrections are required for hydrodynamic stability and causality

W. Israel, J. M. Stewart, Annals Phys 118, 341 (1979)
W.A. Hiscock, L. Lindblom, Phys. Rev. D 31, 725 (1985)

Dissipative hydrodynamics

- Israel-Stewart theory with net charges?

  - The entropy production

$$\partial_\mu s^\mu = -\sum_i \int \frac{g_i d^3 p_i}{(2\pi)^3 E_i} p_i^\mu \frac{\partial \phi}{\partial f^i} \partial_\mu f^i = \boxed{\sum_i \int \frac{g_i d^3 p_i}{(2\pi)^3 E_i} p_i^\mu y^i \partial_\mu f^i} \geqq 0$$

where $\phi(f^i) \equiv f^i \ln f^i - \epsilon^{-1}(1+\epsilon f^i)\ln(1+\epsilon f^i)$, $f^i = \frac{1}{\exp(y^i) \mp 1}$

  - Assume the deviation $\delta y^i = y^i - y_0^i$ is expressed as

$$\delta y^i = p_i^\mu q_i^J \varepsilon_\mu^J + p_i^\mu p_i^\nu \varepsilon_{\mu\nu}$$

(Cf. $y_0^i = q_i^J \frac{\mu_J}{T} + p_i^\mu \frac{u_\mu}{T}$)

*Grad's moment method extended to multi-conserved current systems

$$\boxed{\begin{aligned} \varepsilon_{\mu\nu} &= (B_\Pi \Pi + B_{\delta e}\delta e + \sum_J B_{\delta n_J}\delta n_J)\Delta_{\mu\nu} + (\tilde{B}_\Pi \Pi + \tilde{B}_{\delta e}\delta e + \sum_J \tilde{B}_{\delta n_J}\delta n_J) u_\mu u_\nu \\ &\quad + 2B_W u_{(\mu}W_{\nu)} + 2\sum_J B_{V_J} u_{(\mu}V_{\nu)}^J + B_\pi \pi_{\mu\nu} \\ \varepsilon_\mu^J &= (D_\Pi^J \Pi + D_{\delta e}^J \delta e + \sum_K D_{\delta n_K}^J \delta n_K) u_\mu + D_W^J W_\mu + \sum_K D_{V_K}^J V_\mu^K \end{aligned}}$$

Dissipative hydrodynamics

- Israel-Stewart theory with net charges

▶ The entropy production up to the 2nd order

$$\partial_\mu s^\mu = \sum_i \int \frac{g_i d^3p}{(2\pi)^3 E_i} (y_0 + \delta y) p_i^\mu \partial_\mu (f_0^i + \delta f_i)$$

$$= \sum_J \varepsilon_\nu^J \sum_i \int \frac{q_i^J g_i d^3p}{(2\pi)^3 E_i} p_i^\mu p_i^\alpha \partial_\alpha f_0^i + \sum_J \varepsilon_\nu^J \sum_i \int \frac{q_i^J g_i d^3p}{(2\pi)^3 E_i} p_i^\mu p_i^\alpha \partial_\alpha \delta f^i$$

$$+ \varepsilon_{\nu\rho} \sum_i \int \frac{g_i d^3p}{(2\pi)^3 E_i} p_i^\mu p^\nu p_i^\alpha \partial_\alpha f_0^i + \varepsilon_{\nu\rho} \sum_i \int \frac{g_i d^3p}{(2\pi)^3 E_i} p_i^\mu p^\nu p_i^\alpha \partial_\alpha \delta f^i$$

Traditional I-S theory

equivalent to linear response theory

$$\partial_\mu s^\mu = \delta e D\frac{1}{T} - \Pi \frac{1}{T}\nabla_\mu u^\mu + W^\mu \left(\nabla_\mu \frac{1}{T} + \frac{1}{T} D u_\mu\right) + \pi^{\mu\nu}\frac{1}{T}\nabla_{\langle\mu}u_{\nu\rangle} - \sum_J \delta n_J D\frac{\mu_J}{T} - \sum_J V_J^\mu \nabla_\mu \frac{\mu_J}{T}$$

Semi-positive definite condition

2nd order dissipative fluid dynamic equations

Dissipative hydrodynamics

- Relativistic hydrodynamic equations

Conservation laws $\partial_\mu T^{\mu\nu} = 0 \quad \partial_\mu N_B^\mu = 0$ +

$$D = u^\mu \partial_\mu$$
$$\nabla^\mu = \partial^\mu - u^\mu D$$

The law of increasing entropy -> Constitutive equations

$$\Pi = -\zeta \nabla_\mu u^\mu - \zeta_{\Pi\delta e} D\frac{1}{T} + \zeta_{\Pi\delta n_B} D\frac{\mu_B}{T} - \tau_\Pi D\Pi + \chi^a_{\Pi\Pi}\Pi D\frac{\mu_B}{T} + \chi^b_{\Pi\Pi}\Pi D\frac{1}{T} + \chi^c_{\Pi\Pi}\Pi\nabla_\mu u^\mu$$
$$+ \chi^a_{\Pi V} V_\mu \nabla^\mu \frac{\mu_K}{T} + \chi^b_{\Pi V} V_\mu \nabla^\mu \frac{1}{T} + \chi^c_{\Pi V} V_\mu D u^\mu + \chi^d_{\Pi V}\nabla^\mu V_\mu + \chi_{\Pi\pi}\pi_{\mu\nu}\nabla^{\langle\mu}u^{\nu\rangle}$$

$$V^\mu = \kappa_V \nabla^\mu \frac{\mu_B}{T} - \kappa_{VW}\left(\frac{1}{T}Du^\mu + \nabla^\mu\frac{1}{T}\right) - \tau_V \Delta^{\mu\nu} D V_\nu + \chi^a_{VV} V^\mu_K D\frac{\mu_B}{T} + \chi^b_{VV} V^\mu D\frac{1}{T}$$
$$+ \chi^c_{V_J V} V^\mu \nabla_\nu u^\nu + \chi^d_{VV} V^\nu_K \nabla_\nu u^\mu + \chi^e_{VV} V^\nu \nabla^\mu u_\nu + \chi^a_{V\pi}\pi^{\mu\nu}\nabla_\nu \frac{\mu_B}{T} + \chi^b_{V\pi}\pi^{\mu\nu}\nabla_\nu\frac{1}{T}$$
$$+ \chi^c_{V\pi}\pi^{\mu\nu} D u_\nu + \chi^d_{V\pi}\Delta^{\mu\nu}\nabla^\rho \pi_{\nu\rho} + \chi^a_{V\Pi}\Pi\nabla^\mu\frac{\mu_B}{T} + \chi^b_{V\Pi}\Pi\nabla^\mu\frac{1}{T} + \chi^c_{V\Pi}\Pi D u^\mu + \chi^d_{V\Pi}\nabla^\mu\Pi$$

$$\pi^{\mu\nu} = 2\eta\nabla^{\langle\mu}u^{\nu\rangle} - \tau_\pi D\pi^{\langle\mu\nu\rangle} + \chi_{\pi\Pi}\Pi\nabla^{\langle\mu}u^{\nu\rangle} + \chi^a_{\pi\pi}\pi^{\mu\nu} D\frac{\mu_B}{T} + \chi^b_{\pi\pi}\pi^{\mu\nu} D\frac{1}{T} + \chi^c_{\pi\pi}\pi^{\mu\nu}\nabla_\rho u^\rho$$
$$+ \chi^d_{\pi\pi}\pi^{\rho\langle\mu}\nabla_\rho u^{\nu\rangle} + \chi^{aJ}_{\pi V} V^{\langle\mu}\nabla^{\nu\rangle}\frac{\mu_B}{T} + \chi^b_{\pi V} V^{\langle\mu}\nabla^{\nu\rangle}\frac{1}{T} + \chi^c_{\pi V} V^{\langle\mu} D u^{\nu\rangle} + \chi^d_{\pi V}\nabla^{\langle\mu}V^{\nu\rangle}$$

Simulation Setup

- Equation of state: Lattice QCD with Taylor expansion

$$\frac{P(T,\mu_B)}{T^4} = \frac{P(T,0)}{T^4} + \frac{\chi_B^{(2)}(T,0)}{2}\left(\frac{\mu_B}{T}\right)^2 + \mathcal{O}\left(\frac{\mu_B}{T}\right)^4$$

$P(T,0)$: Equation of state at vanishing μ_B — S. Borsanyi *et al.*, JHEP 1011, 077

$\chi_B^{(2)}(T,0)$: 2nd order baryon fluctuation — S. Borsanyi *et al.*, JHEP 1201, 138

- Transport coefficients: AdS/CFT + phenomenology

Shear viscosity: $\eta = s/4\pi$ — P. Kovtun *et al.*, PRL 94, 111601

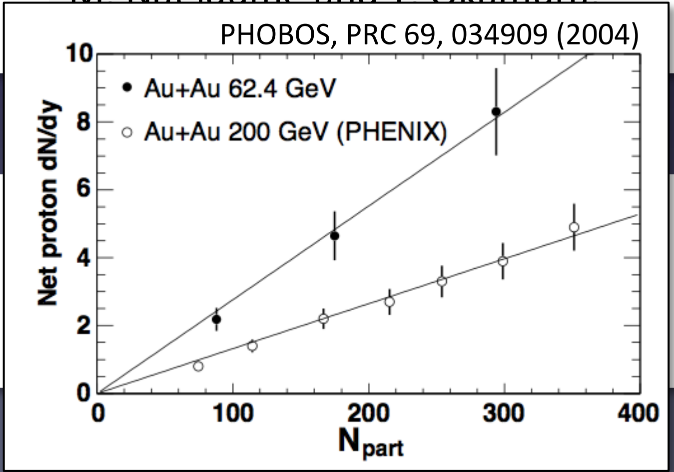
Bulk viscosity: $\zeta = 5(\frac{1}{3} - c_s^2)\eta$ — A. Hosoya *et al.*, AP 154, 229

Baryon dissipation: $\kappa_V = \frac{c_V}{2\pi}(\frac{\partial \mu_B}{\partial n_B})_T^{-1}$ — M. Natsuume and T. Okamura

- Initial conditions: Color glass theory

Energy density: MC-KLN

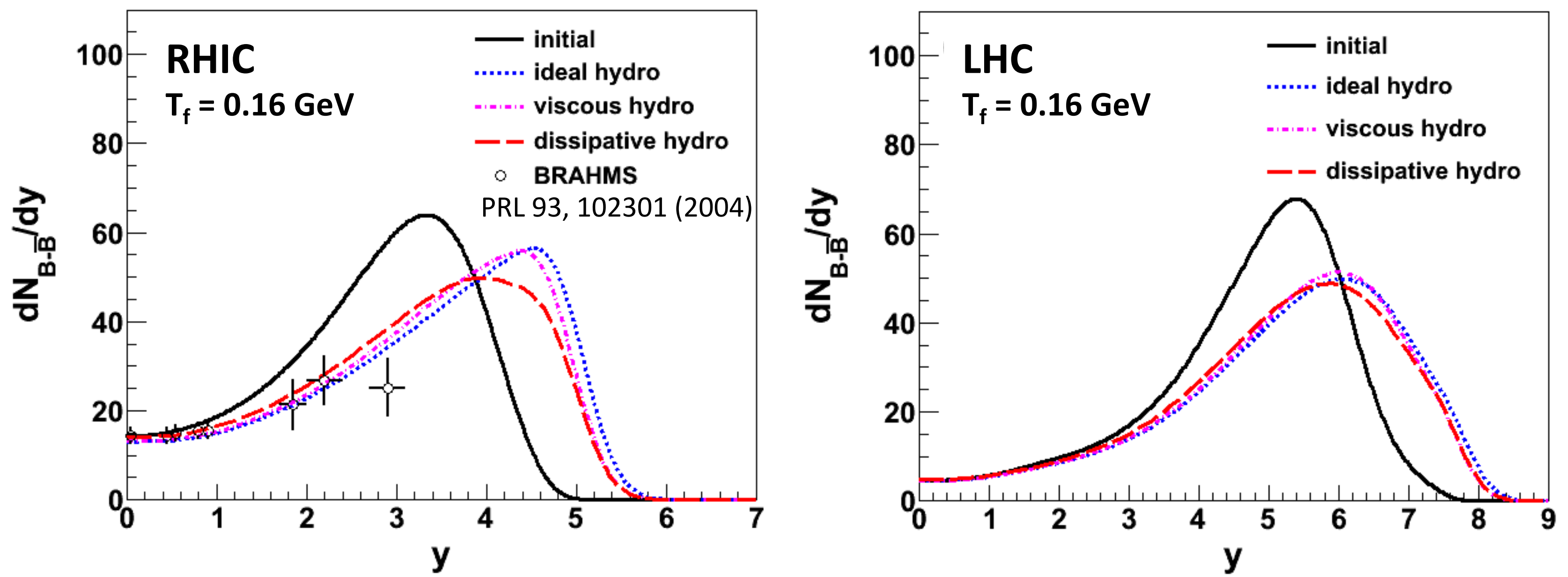
Net baryon density: Valence quark dist.



- Geometry: (1+1)-D expansion

Results

- Net baryon rapidity distribution at RHIC and LHC



- Hydrodynamic evolution sends the net baryon number to forward rapidity
- Viscosities/dissipation could be non-negligible at RHIC

Results

- Mean rapidity loss at RHIC

Mean rapidity loss $\langle \delta y \rangle = y_p - \langle y \rangle$

$$\langle y \rangle = \int_0^{y_p} y \frac{dN_{B-\bar{B}}(y)}{dy} dy \Big/ \int_0^{y_p} \frac{dN_{B-\bar{B}}(y)}{dy} dy$$

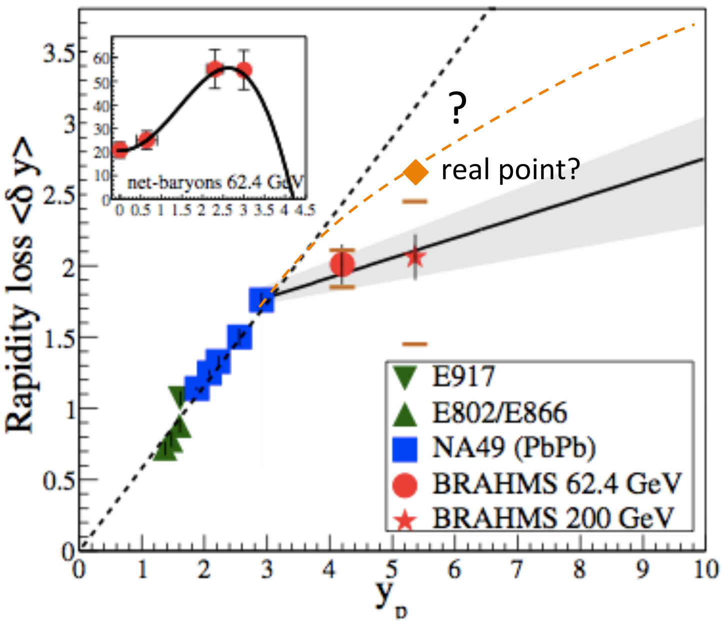
Initial loss (RHIC): $\langle \delta y \rangle = 2.67$

Ideal hydro: $\langle \delta y \rangle = 2.09$

Viscous hydro: $\langle \delta y \rangle = 2.16$

Dissipative hydro: $\langle \delta y \rangle = 2.26$

BRHAMS, PLB 677, 267 (2009)

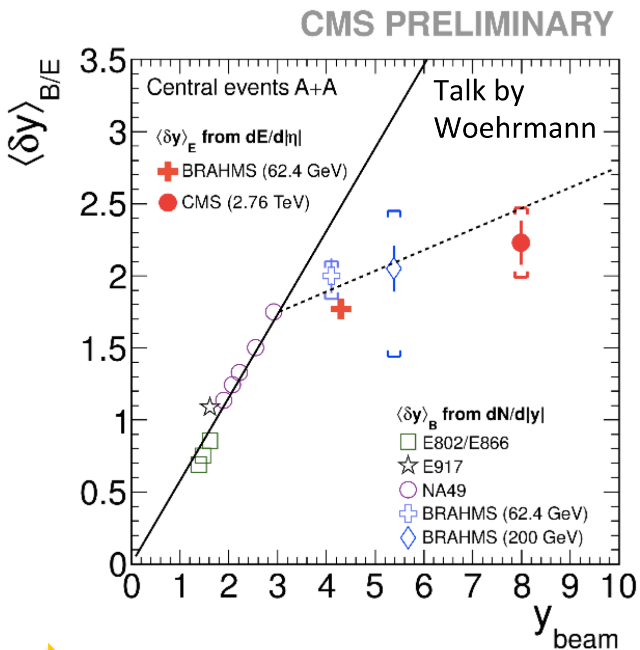


- Transparency of the collision is effectively enhanced in hydrodynamic evolution

→ More kinetic energy is available for QGP production

Discussion

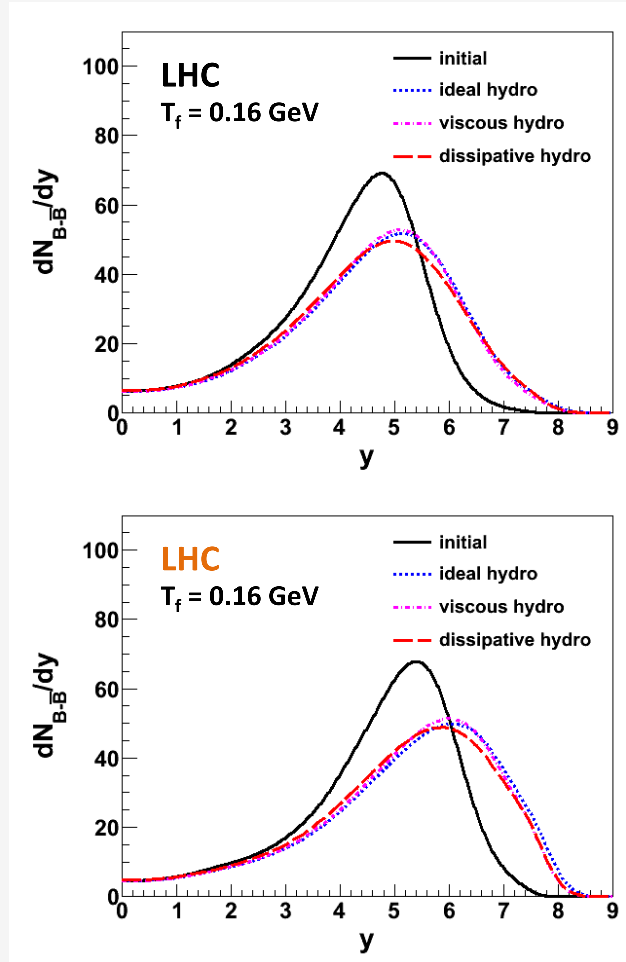
- New implications from LHC



More transparent initial conditions are preferred

Note: a *different* observable

$$\langle \delta y \rangle_{\mathrm{E}} = \frac{2}{E_{\mathrm{N}} N_{\mathrm{part}}} \int_{\infty}^{-y_{\mathrm{beam}}} y\prime \frac{\mathrm{d}E}{\mathrm{d}y\prime} \mathrm{d}y\prime$$



Initial loss : 3.88

Ideal hydro: 3.44

Viscous: 3.48

Dissipative: 3.51

Initial loss : 3.36

Ideal hydro: 2.81

Viscous: 2.86

Dissipative: 2.92

Cross-coupling effects (1)

- Linear response theory and cross terms

Bulk pressure (w/o charges)

$$\Pi = -\zeta_{\Pi\Pi}\frac{1}{T}\nabla_\mu u^\mu - \zeta_{\Pi\delta e} D\frac{1}{T} = -\underbrace{\left(\frac{\zeta_{\Pi\Pi}}{T} + \frac{\zeta_{\Pi\delta e}}{T}c_s^2\right)}_{\text{bulk viscosity } \zeta}\nabla_\mu u^\mu$$

Response to expansion

Response to cooling

- Response to expansion itself can be as large as shear viscosity
- Cancelled by the cross term except for crossover where $c_s^2 \sim 0$
  - ⇒ A reason for general smallness of bulk viscosity

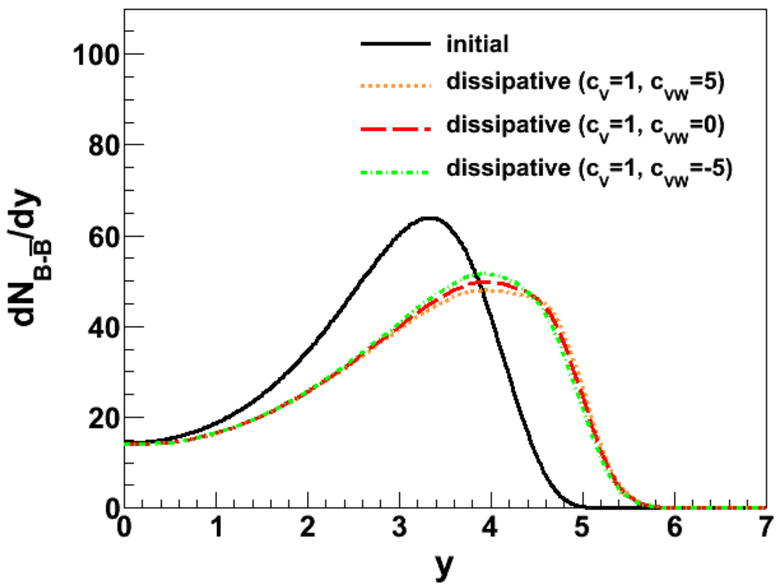
Baryon dissipation current

$$V^\mu = \kappa_V \nabla^\mu \frac{\mu_B}{T} - \kappa_{VW}\left(\nabla^\mu \frac{1}{T} + \frac{1}{T} D u^\mu\right)$$

- Baryon dissipation can be induced by thermal gradient + acceleration

Results

Thermo-diffusion effect (a.k.a. Soret effect)



- Baryon dissipation can be induced by thermal gradients (and acceleration)

$$V^\mu = \kappa_V \nabla^\mu \frac{\mu_B}{T} - \kappa_{VW} \left(\nabla^\mu \frac{1}{T} + \frac{1}{T} D u^\mu \right)$$

at the linear order

- The cross coefficient can be negative

$$\kappa_{VW} = c_{VW} \frac{n_{B0} T}{e_0 + P_0} \sqrt{5 \eta T \kappa_V}$$

▪ The effect of cross coupling is likely to be small in high-energy collisions

because of the matter-antimatter symmetry

$V^\mu(\mu_B) = -V^\mu(-\mu_B)$ which leads to $\kappa_{VW}(\mu_B = 0) = 0$

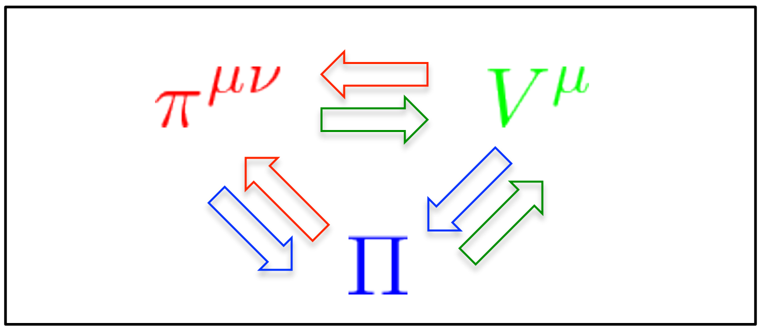
Cross-coupling effects (2)

- Mixing of the currents at the 2nd order

System dependence

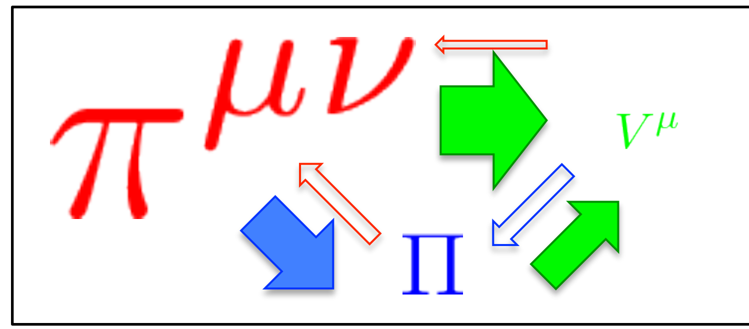
Hydrodynamic theory considers:

$$\pi^{\mu\nu} \sim \Pi \sim V^\mu$$



In high-energy nuclear collisions:

$$\pi^{\mu\nu} > \Pi > V^\mu$$



- Bulk-shear coupling term in bulk pressure
  Baryon-shear and baryon-bulk coupling terms in baryon dissipation
  have more impact than other 2nd order terms (numerically confirmed)
- Applicability of the expansion is dependent on the 2nd order transport coefficients

Brief summary

- Dissipative hydrodynamic model is developed and simulated at finite baryon density
  - Net baryon distribution is widened in hydrodynamic evolution
    - ⇨ Transparency of the collision is effectively enhanced
    - ⇨ More kinetic energy may be available at QGP production in early stage (~ 10% at RHIC)
  - The results are sensitive to baryon diffusion coefficient
    - ⇨ Ambiguities remain in initial condition, but the distribution has important information
- Future prospects include:
  - Estimation of transverse expansion, inclusion of more realistic transport coefficients, etc.

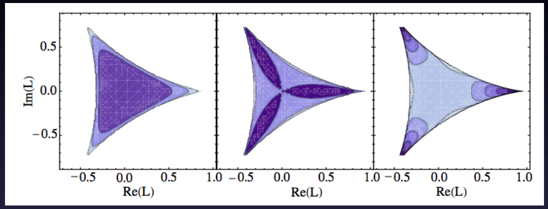
2. Center domain structure in QGP

Reference: K. Kashiwa and AM, arXiv:1309.6742 [hep-ph]

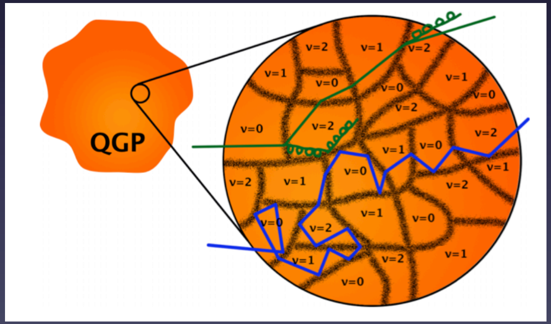
Motivation

- Center domain structure in the QGP   Asakawa, Bass and Müller, PRL 110,201301 (2013)
  - One knows *how*, but not *why* hydrodynamics work so well
  - Z_3 (center) symmetry in pure gauge system
    - ⇨ Three minima separated by energy barriers may exist in the complex plane of Polyakov-loop for the QGP phase

Asakawa, Bass and Müller, PRL 110,201301 (2013)



    - ⇨ Center domain structure can develop in a QCD medium because CGC and glasma imply the typical size of correlation is ~1/Qs

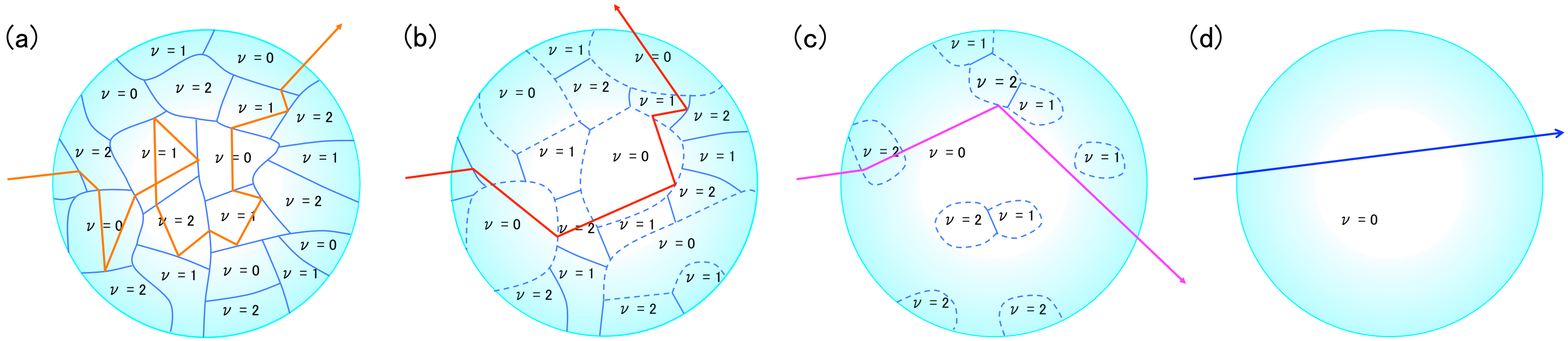


    - ⇨ Mean free path is characterized by the size of domain; small viscosity and large opacity can be explained
  - How does it approach pQCD picture at high T?

Center domain structure

- Quark contribution

K. Kashiwa, AM, arXiv:1309.6742 [hep-ph]



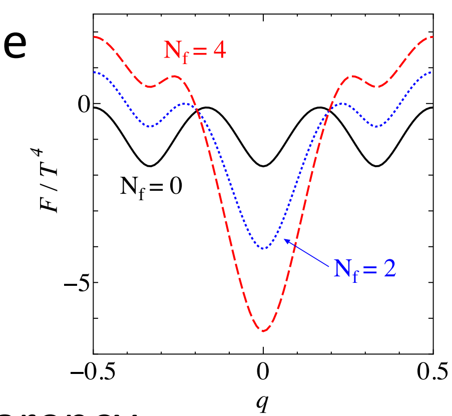
- (a) -> (b) Stable domains expand (ν=0) while metastable ones (ν=1,2) shrink due to pressure imbalance

  ⇨ Mean free path is longer, increasing viscosity

- (b) -> (c) Percolation of stable domains

- (c) -> (d) Metastable states vanish above a critical temperature $T_{cri} = T(P_{1,2} = 0)$; large viscosity and transparency

  ⇨ A smooth bridge from sQGP (hydrodynamics) to wQGP (pQCD)

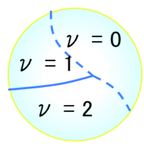


Center domain structure

Quark contribution

K. Kashiwa, AM, arXiv:1309.6742 [hep-ph]

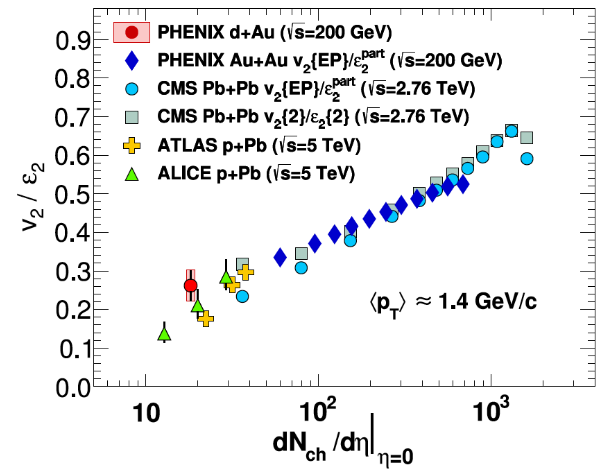
- pp, pA and dA collisions



size of domains ~ 0.5 fm

< radius of a proton ~ 0.8 fm

PHENIX, arXiv:1303.1794 [nucl-ex]



⇨ Several domains (and primordial fluidity) can be developed

The structure might be fragile against finite size effects and quark contribution

- Heavy collisions at higher energies

⇨ Scenarios can be distinguished when above T_{cri} (N_f ~ 3)

Center domain is the origin of fluidity: yes -> small v_2 (ν = 0 everywhere)
no -> large v_2 (in sQGP stage)

Summary and outlook

- Dissipative hydrodynamic model at finite baryon density
  - Baryon stopping is effectively reduced by hydrodynamic flow
    - ⇨ Energy available for QGP production could be larger
  - Net baryon distribution is sensitive to baryon diffusion
  - Future prospects: three dimensional analyses and more realistic transport coefficients for quantitative discussion, etc.
- Center domain structure with quark contribution
  - Provides a bridge from hydrodynamics to pQCD
  - A topological critical temperature may be present near $N_f \sim 3$
  - Future prospects: analyses on system size dependence, boundary effects, etc.

The end

- Thank you for listening!
- Website: http://tkynt2.phys.s.u-tokyo.ac.jp/~monnai/